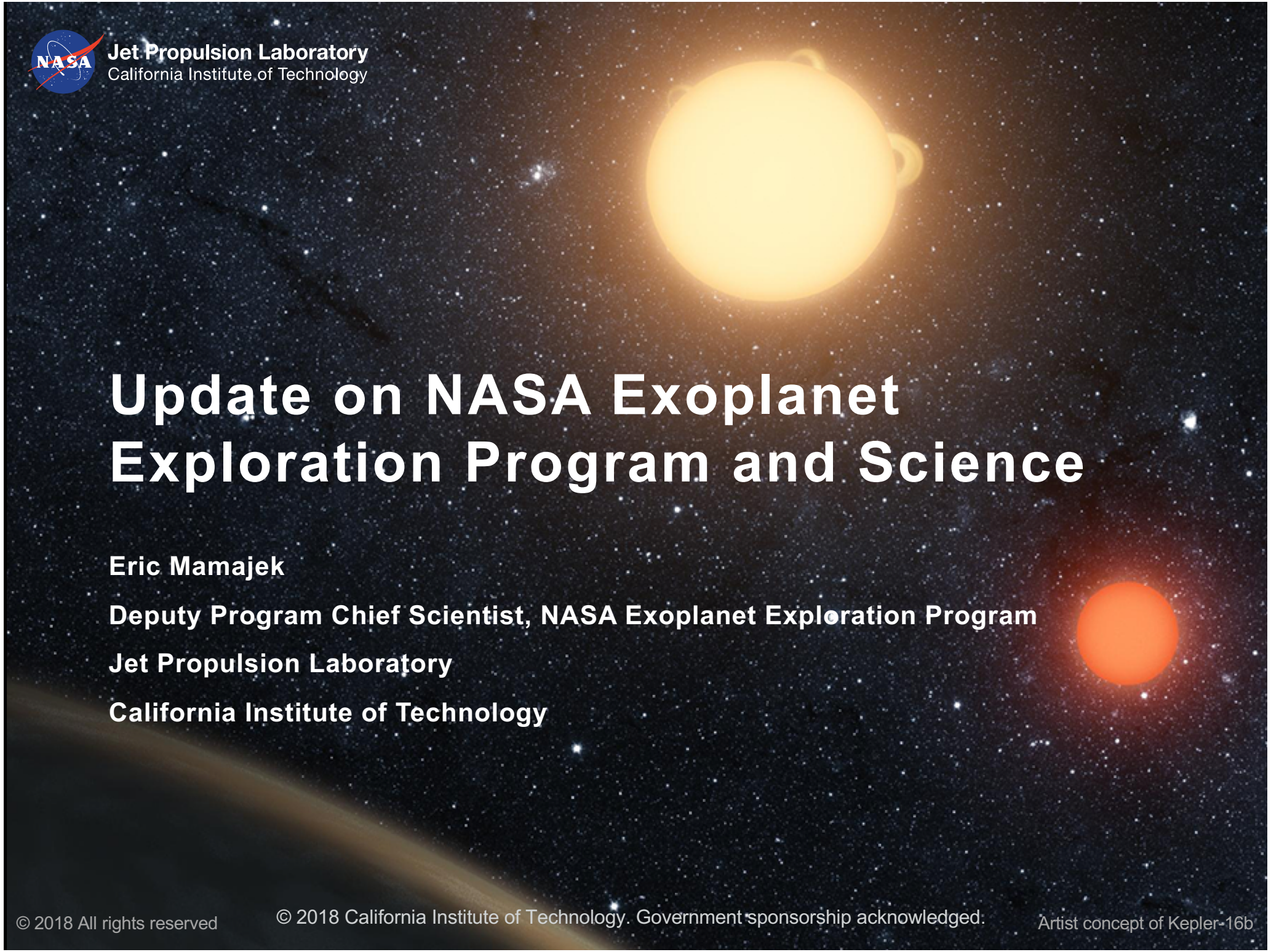
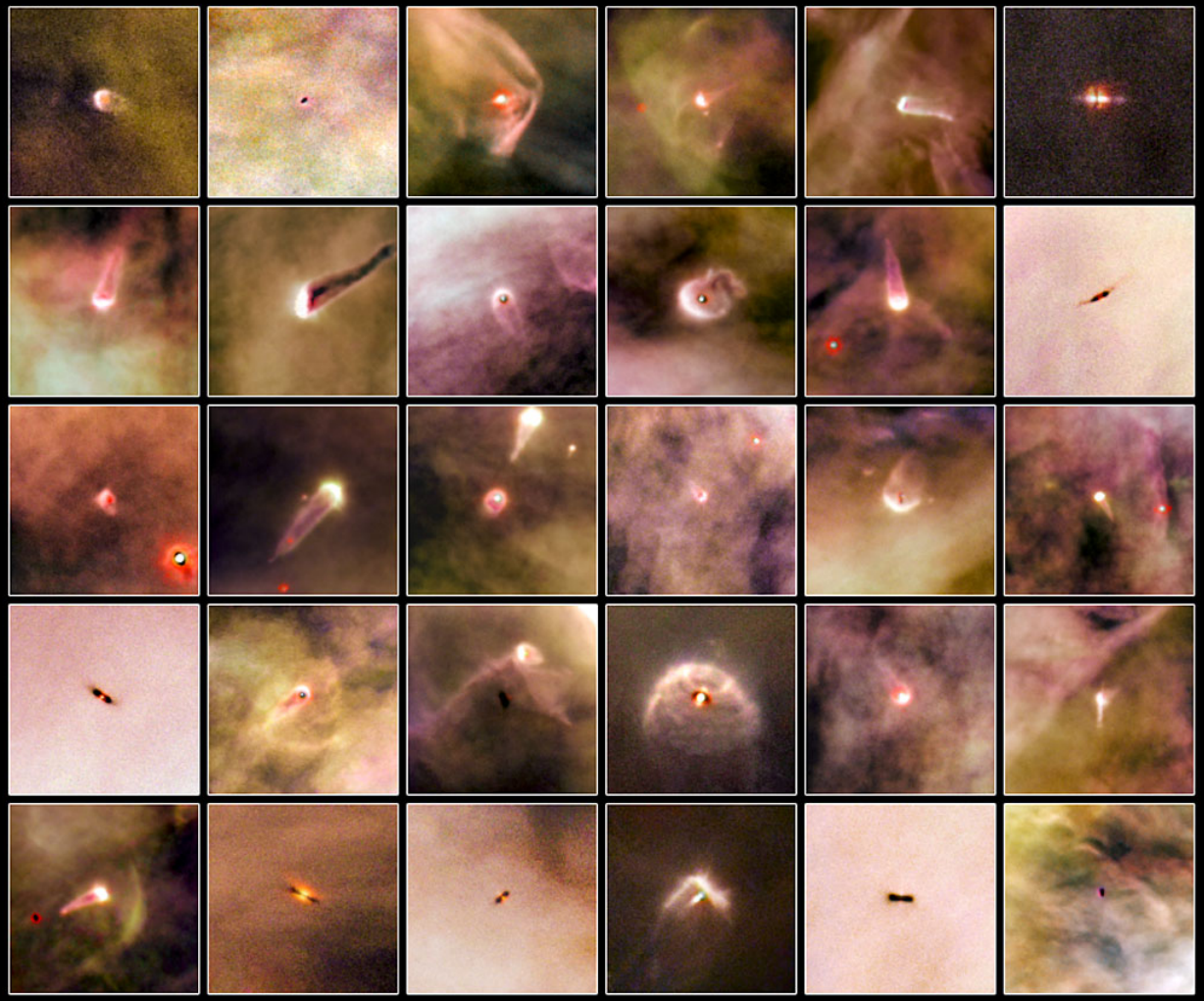

Jet Propulsion Laboratory
California Institute of Technology
Update on NASA Exoplanet Exploration Program and Science
Eric Mamajek
Deputy Program Chief Scientist, NASA Exoplanet Exploration Program
Jet Propulsion Laboratory
California Institute of Technology
© 2018 All rights reserved
© 2018 California Institute of Technology. Government sponsorship acknowledged.
Artist concept of Kepler-16b

Credit: Andreas Papadopoulos

Credit: NASA



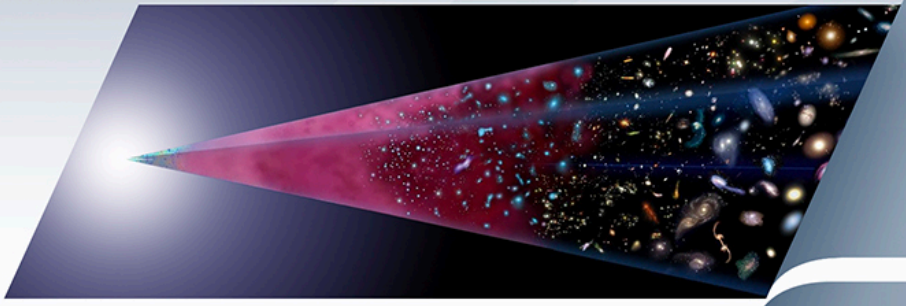
Credit: NASA, ESA, L. Ricci (ESO)


Our nearest stellar neighbors – 4 light years away: The α Centauri triple system
α Cen A/Rigel Kentaurus
α Cen B/Toliman
α Cen C/Proxima Centauri
Exoplanet Proxima Centauri b
Orbital period: 11 days
Orbital separation: 0.05 astronomical unit
Mass: >1.3 Earth mass
Temperature: about 230 K (-40° C)
Doppler amplitude 1.4 meter/second
Credit: ESO/M.Kornmesser

Why Astrophysics?

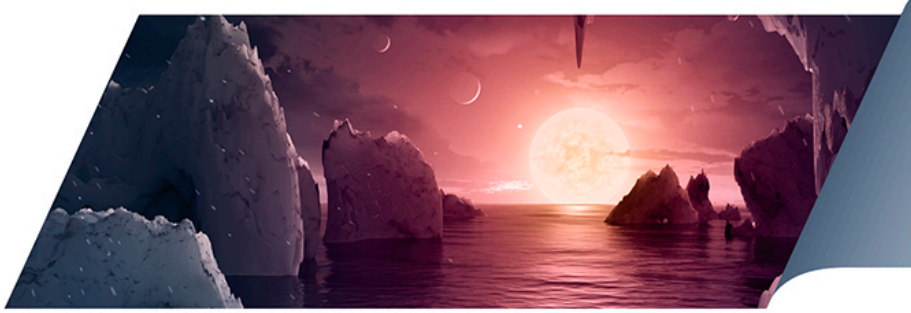
Astrophysics is humankind's scientific endeavor to understand the universe and our place in it.

How did our universe begin and evolve?



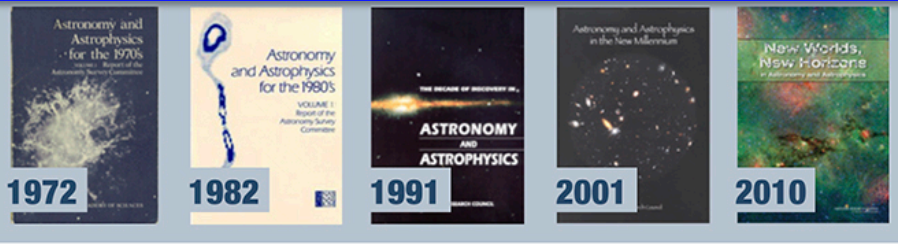
How did galaxies, stars, and planets come to be?

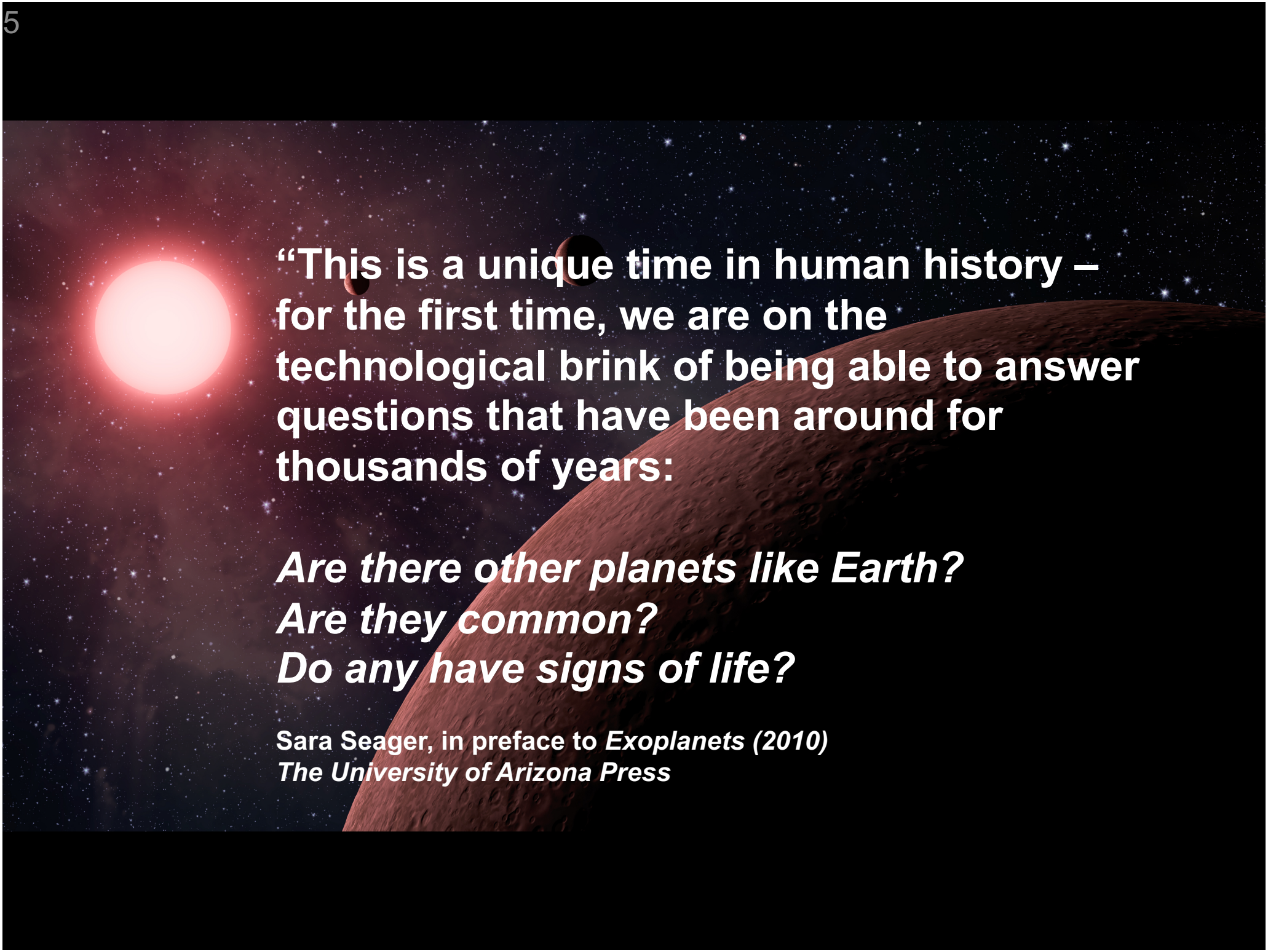
Are we alone?



ExEP

Enduring National Strategic Drivers





"This is a unique time in human history – for the first time, we are on the technological brink of being able to answer questions that have been around for thousands of years:

Are there other planets like Earth?
Are they common?
Do any have signs of life?

Sara Seager, in preface to *Exoplanets (2010)*
The University of Arizona Press

NASA Exoplanet Exploration Program

Astrophysics Division, NASA Science Mission Directorate

NASA's search for habitable planets and life beyond our solar system

Program purpose described in 2014 NASA Science Plan

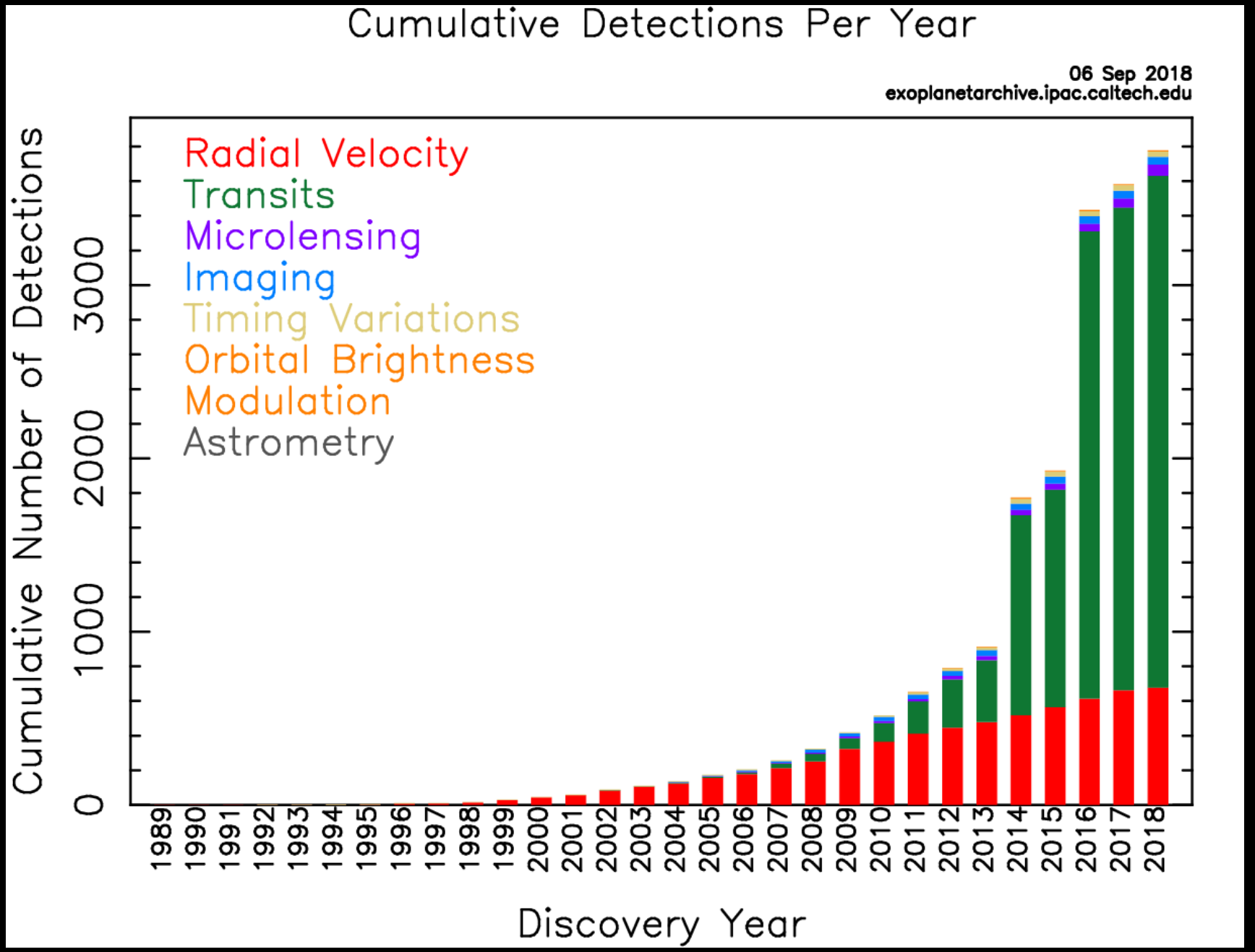
1. Discover planets around other stars
2. Characterize their properties
3. Identify candidates that could harbor life

ExEP serves the science community and NASA by implementing NASA's space science vision for exoplanets

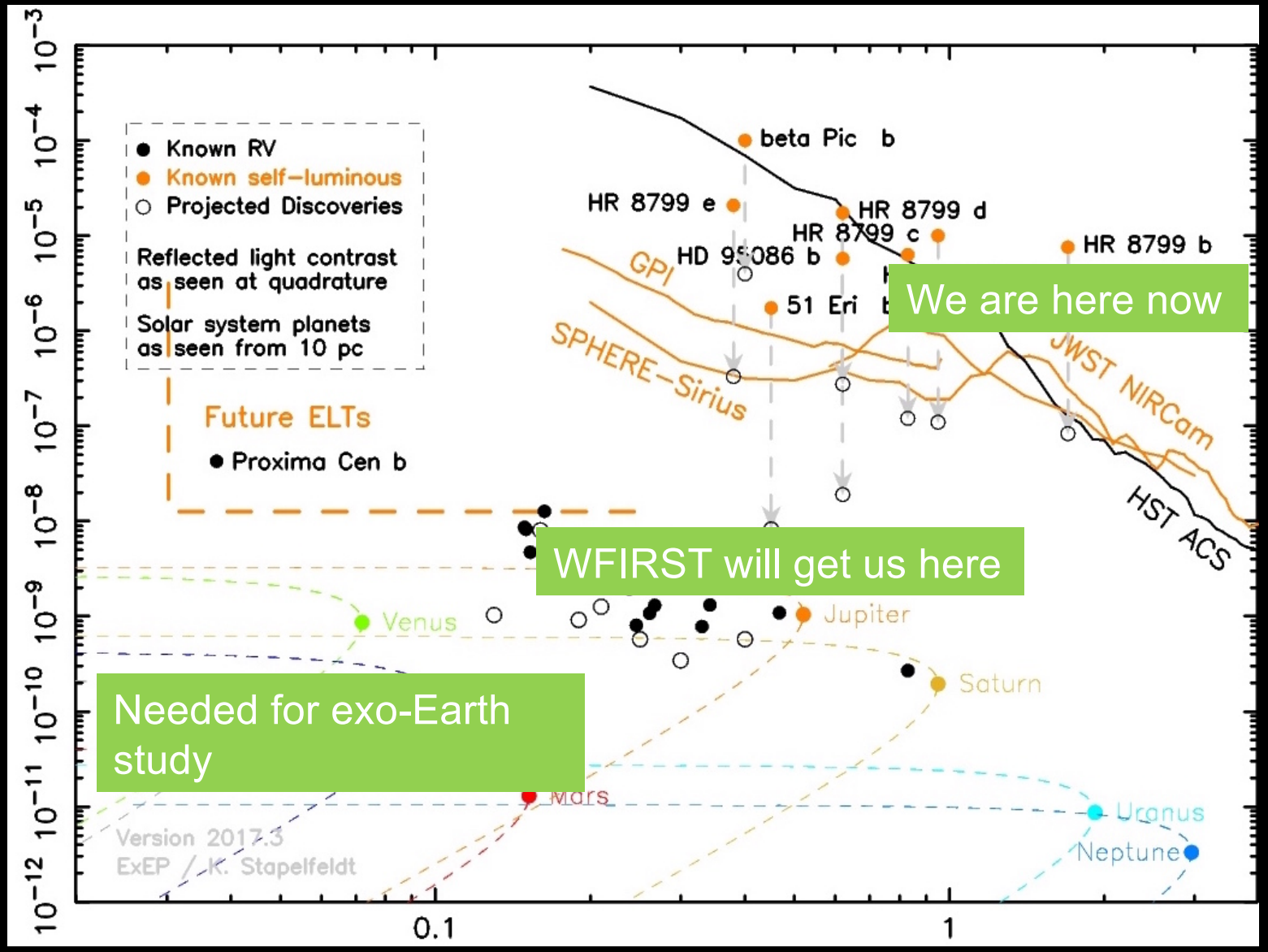
https://exoplanets.nasa.gov

Thousands of Exoplanets

Number doubles every ~27 months.

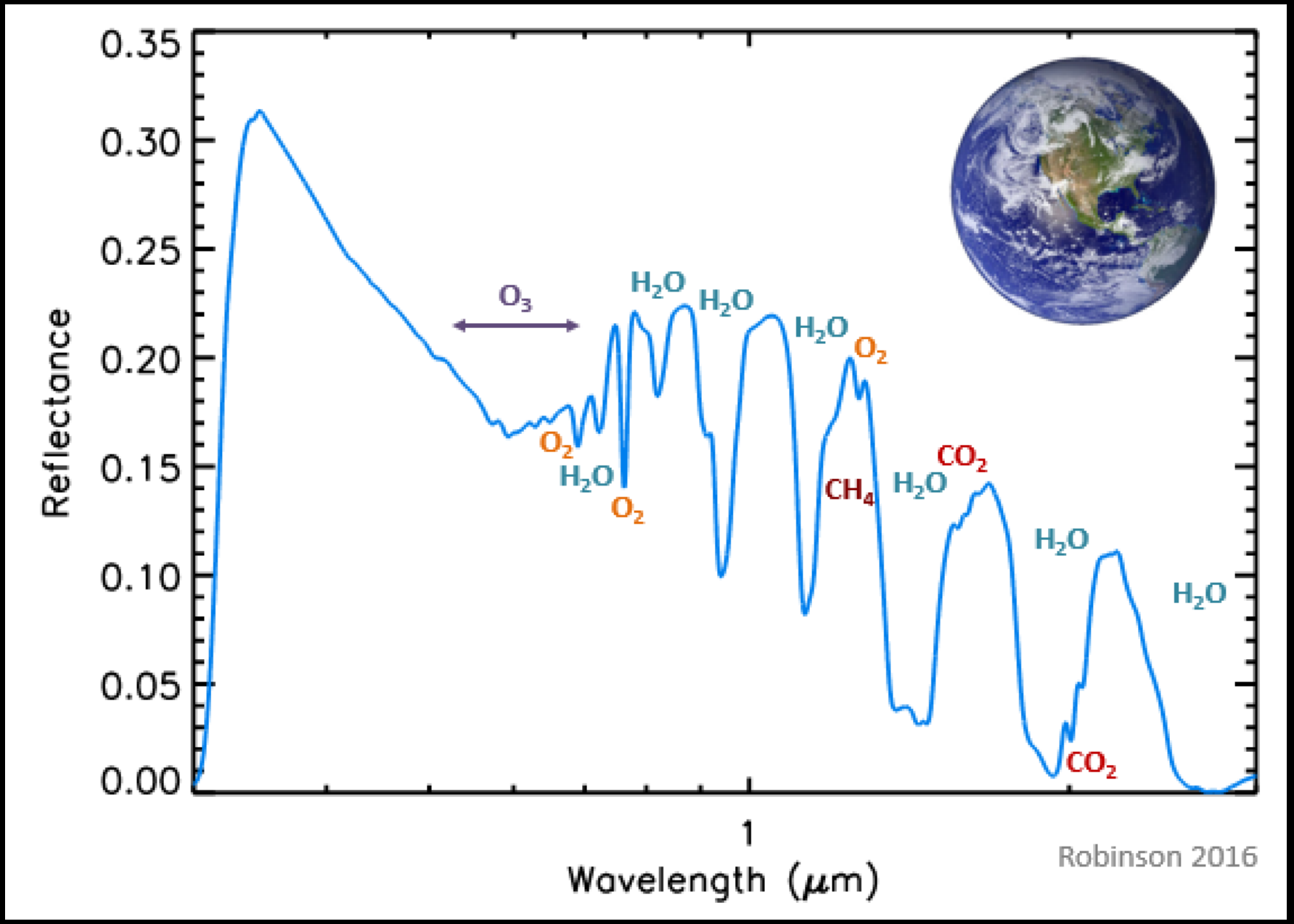


Challenge to Directly Image Exo-Earths

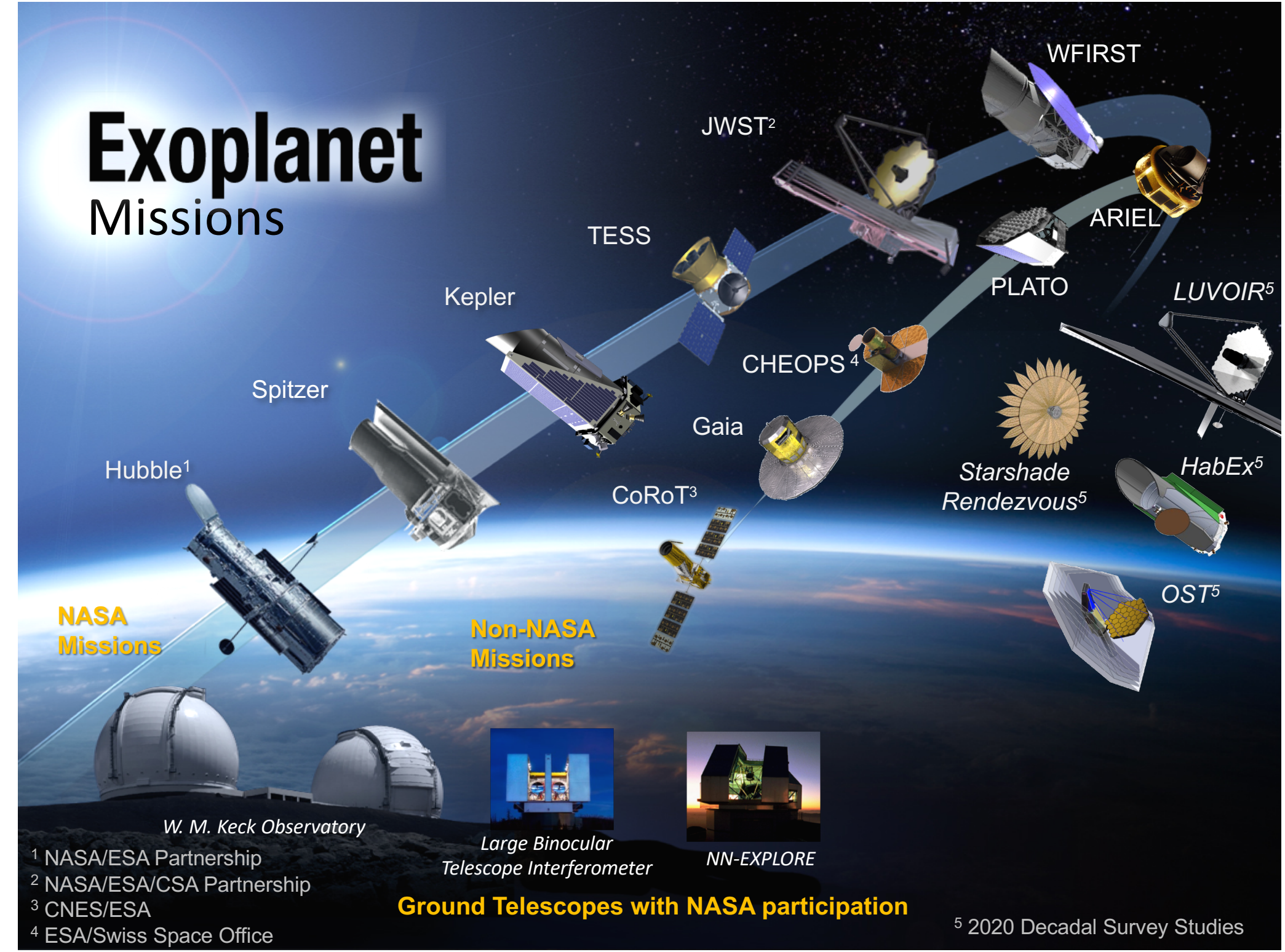


Potential Biosignature Gases

Spectral Lines



Exoplanet Missions



[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA
[4] ESA/Swiss Space Office

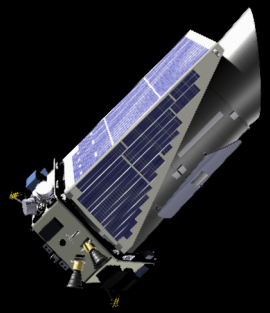
Ground Telescopes with NASA participation

[5] 2020 Decadal Survey Studies

NASA Exoplanet Exploration Program

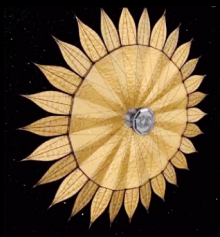
Space Missions and Mission Studies

Kepler & K2

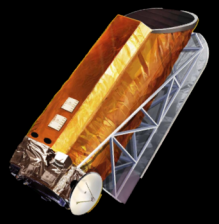


Probe-Scale Studies

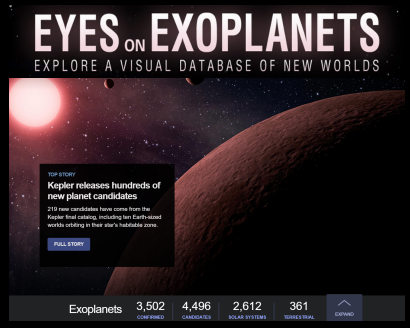
Starshade



Coronagraph

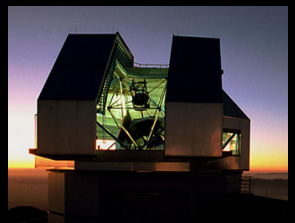


Communications

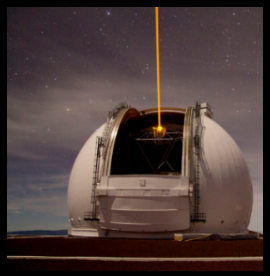


Supporting Research & Technology

Key Sustaining Research



NN-EXPLORE



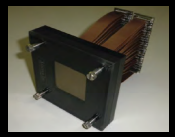
Keck Single Aperture Imaging & RV

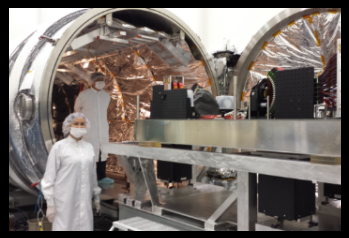
Large Binocular Telescope Interferometer

Technology Development

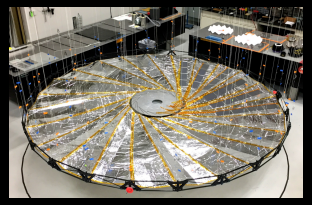
Occulting Masks

Deformable Mirrors



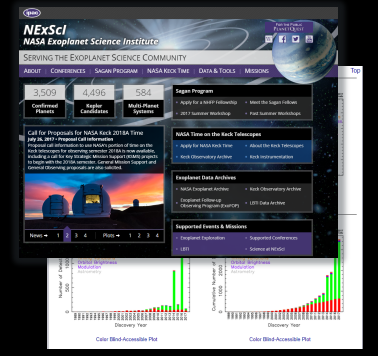


High-Contrast Imaging



Deployable Starshades

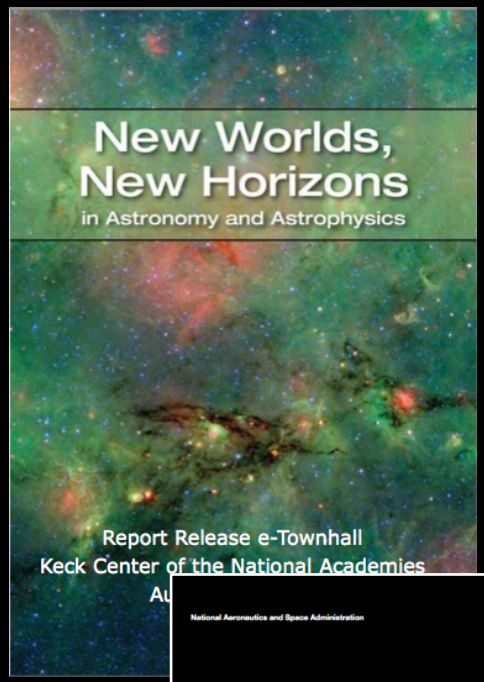
NASA Exoplanet Science Institute



Archives, Tools, Sagan Fellowships, Professional Engagement

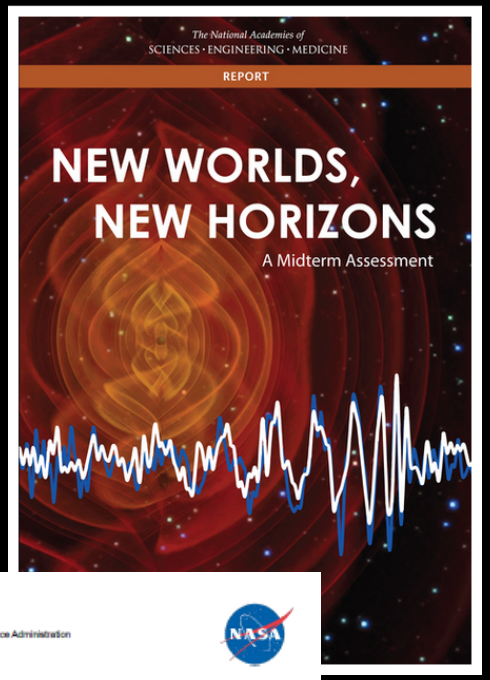
https://exoplanets.nasa.gov

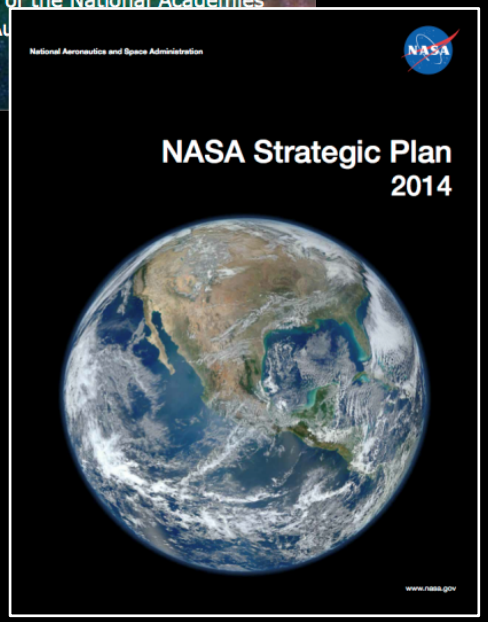
ExEP Implements per NASA Driving Documents

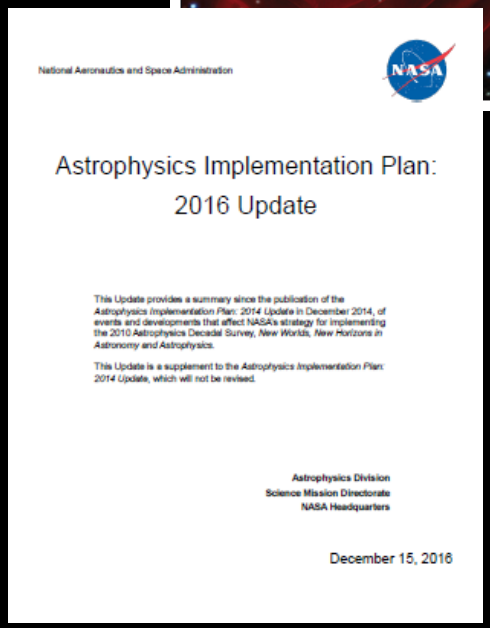


Results of New Worlds, New Horizons (2010 Decadal):

- WFIRST was top large-scale recommended activity
- New Worlds Technology Development Program was top medium-scale recommended activity

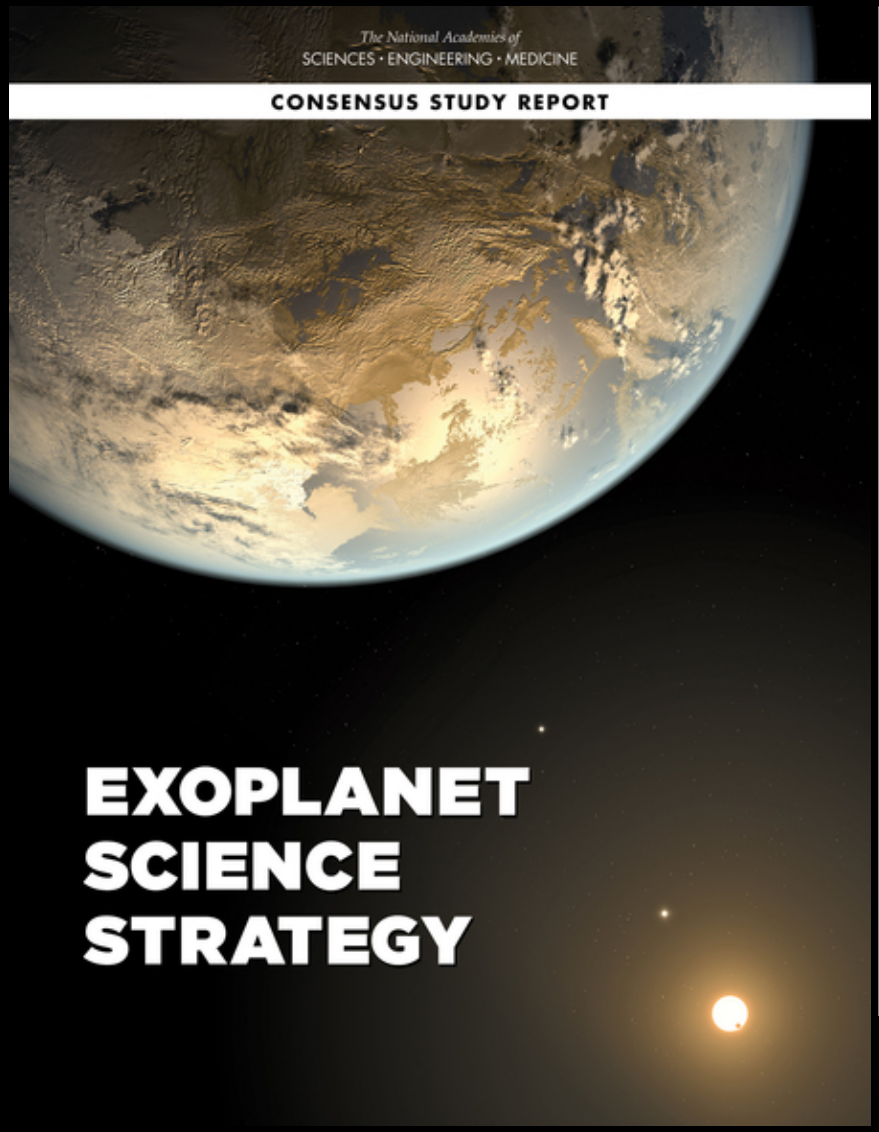






http://science.nasa.gov/astrophysics/documents

Exoplanet Science Strategy (2018)



SEC. 508. EXTRASOLAR PLANET EXPLORATION STRATEGY.

(a) STRATEGY.—

(1) IN GENERAL.—The Administrator shall enter into an arrangement with the National Academies to develop a science strategy for the study and exploration of extrasolar planets, including the use of the Transiting Exoplanet Survey Satellite, the James Webb Space Telescope, a potential Wide-Field Infrared Survey Telescope mission, or any other telescope, spacecraft, or instrument, as appropriate.

(2) REQUIREMENTS.—The strategy shall—

(A) outline key scientific questions;

(B) identify the most promising research in the field;

(C) indicate the extent to which the mission priorities in existing decadal surveys address the key extrasolar planet research and exploration goals;

(D) identify opportunities for coordination with international partners, commercial partners, and not-for-profit partners; and

(E) make recommendations regarding the activities under subparagraphs (A) through (D), as appropriate.

(b) USE OF STRATEGY.—The Administrator shall use the strategy—

(1) to inform roadmaps, strategic plans, and other activities of the Administration as they relate to extrasolar planet research and exploration; and

(2) to provide a foundation for future activities and initiatives related to extrasolar planet research and exploration.

(c) REPORT TO CONGRESS.—Not later than 18 months after the date of enactment of this Act, the National Academies shall submit to the Administrator and to the appropriate committees of Congress a report containing the strategy developed under subsection (a).

NASA Auth. Bill S.442 (2017)

http://sites.nationalacademies.org/SSB/CurrentProjects/SSB_180659

Exoplanet Science Strategy (2018) key recommendations:

Recommendation: ***NASA*** *should lead a large strategic direct imaging mission capable of measuring the reflected-light spectra of temperate terrestrial planets orbiting Sun-like stars.*

Recommendation: *The National Science Foundation should invest in both the GMT and TMT and their exoplanet instrumentation to provide all-sky access to the U.S. community.*

Recommendation: ***NASA*** *should launch WFIRST to conduct its microlensing survey of distant planets and to demonstrate the technique of coronagraphic spectroscopy on exoplanet targets.*

Recommendation: ***NASA*** *and NSF should establish a strategic initiative in extremely precise radial velocities (EPRVs) to develop methods and facilities for measuring the masses of temperate terrestrial planets orbiting Sun-like stars.*

Recommendation: ***NASA*** *should create a mechanism for community-driven legacy surveys of exoplanet atmospheres early in the JWST mission.*

Recommendation: *Building on the NExSS model,* ***NASA*** *should support a cross-divisional exoplanet research coordination network that includes additional membership opportunities via dedicated proposal calls for interdisciplinary research.*

Recommendation: ***NASA*** *should support a robust individual investigator program that includes grants for theoretical, laboratory, and ground-based telescopic investigations; otherwise, the full scientific yield of exoplanet missions will not be realized.*

Astrobiology Science Strategy for the Search for Life in the Universe (2018) key recommendations:

Recommendation: *NASA and other relevant agencies should catalyze research focused on emerging systems-level thinking about dynamic habitability and the coevolution of planets and life, with a focus on problems and not disciplines—that is, using and expanding successful programmatic mechanisms that foster interdisciplinary and cross-divisional collaboration.*

Recommendation: *NASA's programs and missions should reflect a dedicated focus on research and exploration of subsurface habitability in light of recent advances demonstrating the breadth and diversity of life in Earth's subsurface, the history and nature of subsurface fluids on Mars, and potential habitats for life on ocean worlds.*

Recommendation: ***NASA should implement high-contrast starlight suppression technologies in near-term space- and ground-based direct imaging missions.***

Recommendation: *The search for life beyond Earth requires more sophisticated frameworks for considering the potential for non-terran life; therefore, NASA should support research on novel and/or agnostic biosignatures.*

Recommendation: *NASA should direct the community's focus to address important gaps in understanding the breadth, probability, and distinguishing environmental contexts of abiotic phenomena that mimic biosignatures.*

Recommendation: *NASA should support expanding biosignature research to addressing gaps in understanding biosignature preservation and the breadth of possible false positives and false negative signatures.*

Recommendation: *NASA should support the community in developing a comprehensive framework for assessment—including the potential for abiosignatures, false positives, and false negatives—to guide testing and evaluation of in situ and remote biosignatures.*

Recommendation: *To advance the search for life in the universe, NASA should accelerate the development and validation, in relevant environments, of mission-ready, life detection technologies. In addition, it should integrate astrobiological expertise in all mission stages— from inception and conceptualization to planning, development, and operations.*

Recommendation: *NASA should actively seek new mechanisms to reduce the barriers to collaboration with private and philanthropic entities, and with international space agencies, to achieve its objective of searching for life in the universe.*

From NAS Exoplanet Science Strategy (2018)

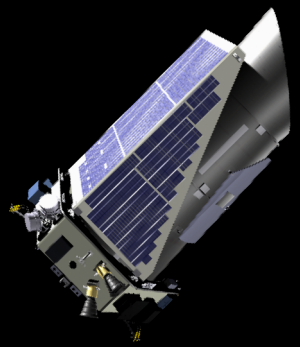
Measurements over the past decade have dramatically reduced three major risk factors identified in the 2010 Astronomy and Astrophysics Decadal Survey for a planet-imaging mission. First, abundance statistics from Kepler strongly suggest that terrestrial planets are common in the habitable zones of stars similar to the Sun. Second, Large Binocular Telescope Interferometer (LBTI) measurements and upper limits for exozodiacal dust in habitable zones indicate that dust is unlikely to prevent optical characterization of planets in most systems. Finally, coronagraph and starshade technologies have advanced substantially, and designing starlight suppression systems that perform at levels necessary for an imaging mission is now practical.

https://www.nap.edu/catalog/25187/exoplanet-science-strategy

From NAS Exoplanet Science Strategy (2018)

Measurements over the past decade have dramatically reduced three major risk factors identified in the 2010 Astronomy and Astrophysics Decadal Survey for a planet-imaging mission. First, abundance statistics from Kepler strongly suggest that terrestrial planets are common in the habitable zones of stars similar to the Sun. Second, Large Binocular Telescope Interferometer (LBTI) measurements and upper limits for exozodiacal dust in habitable zones indicate that dust is unlikely to prevent optical characterization of planets in most systems. Finally, coronagraph and starshade technologies have advanced substantially, and designing starlight suppression systems that perform at levels necessary for an imaging mission is now practical.

Kepler & K2

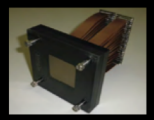


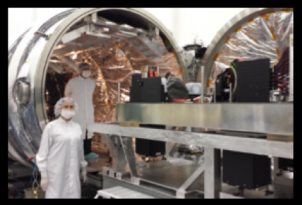
Large Binocular Telescope Interferometer

Technology Development

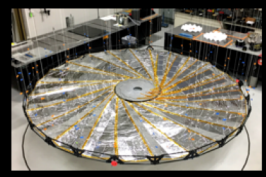
Occulting Masks

Deformable Mirrors





High-Contrast Imaging



Deployable Starshades

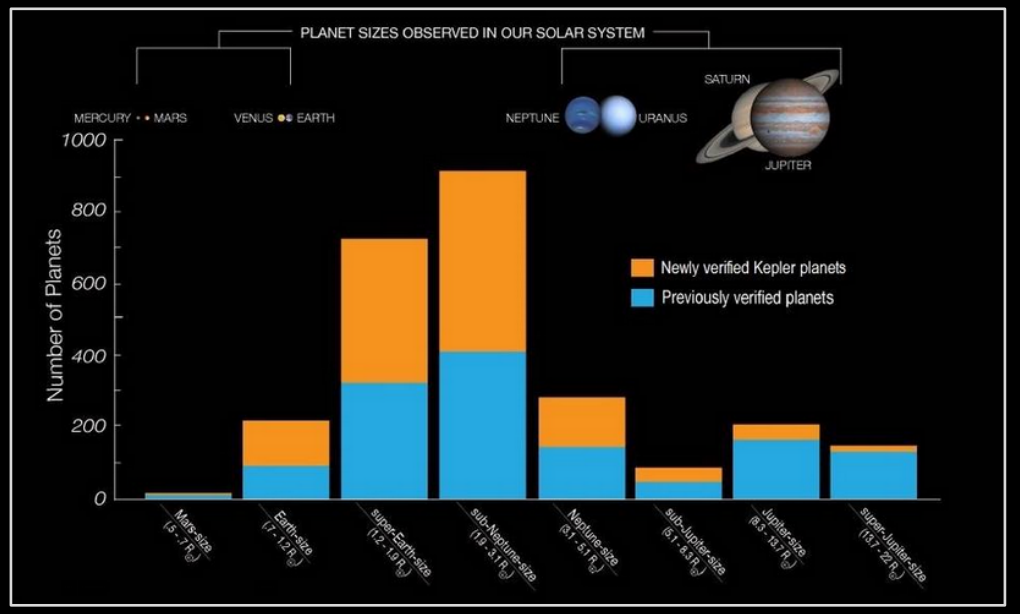
https://www.nap.edu/catalog/25187/exoplanet-science-strategy

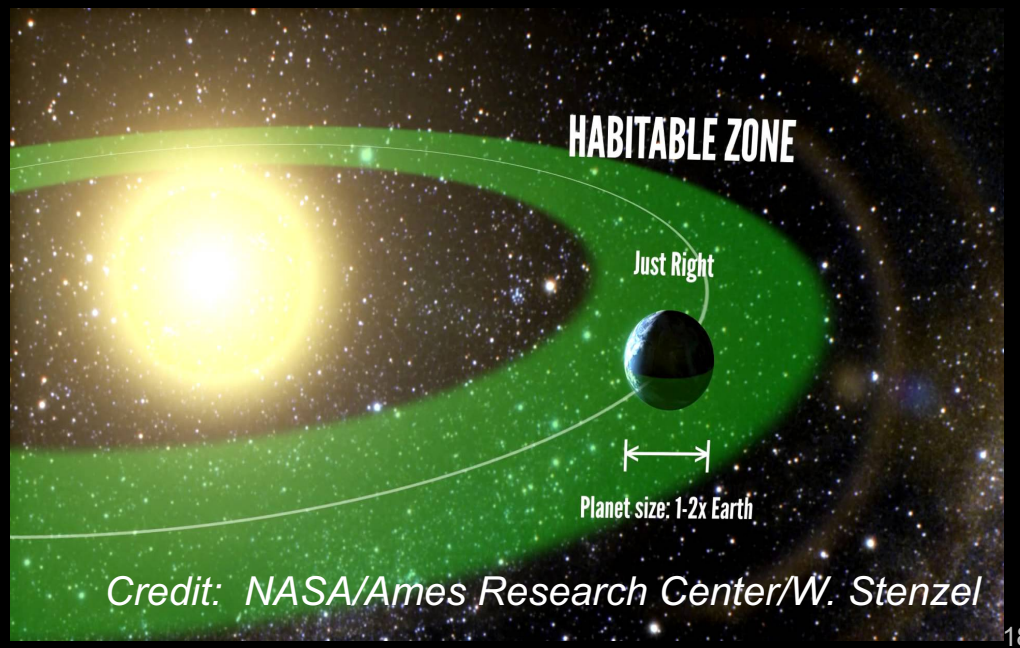
Three Key Kepler Results

1. On average there is at least one planet for each of the stars in the night sky

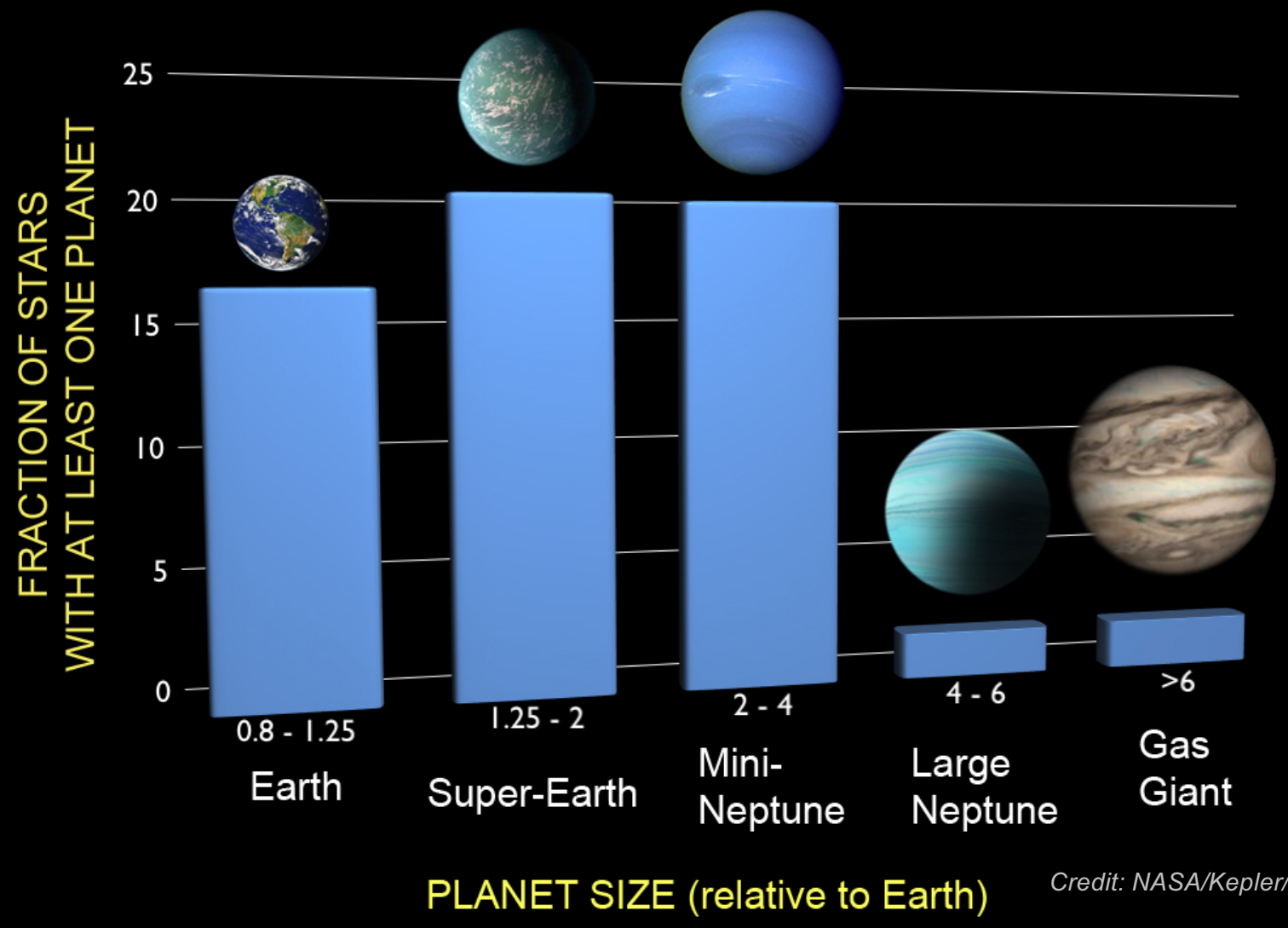
2. Small planets are the most common type in the Galaxy

3. Earth-sized (0.5 to 2 Earth radii) planets in the Habitable Zone are common





Credit: NASA/Ames Research Center/W. Stenzel

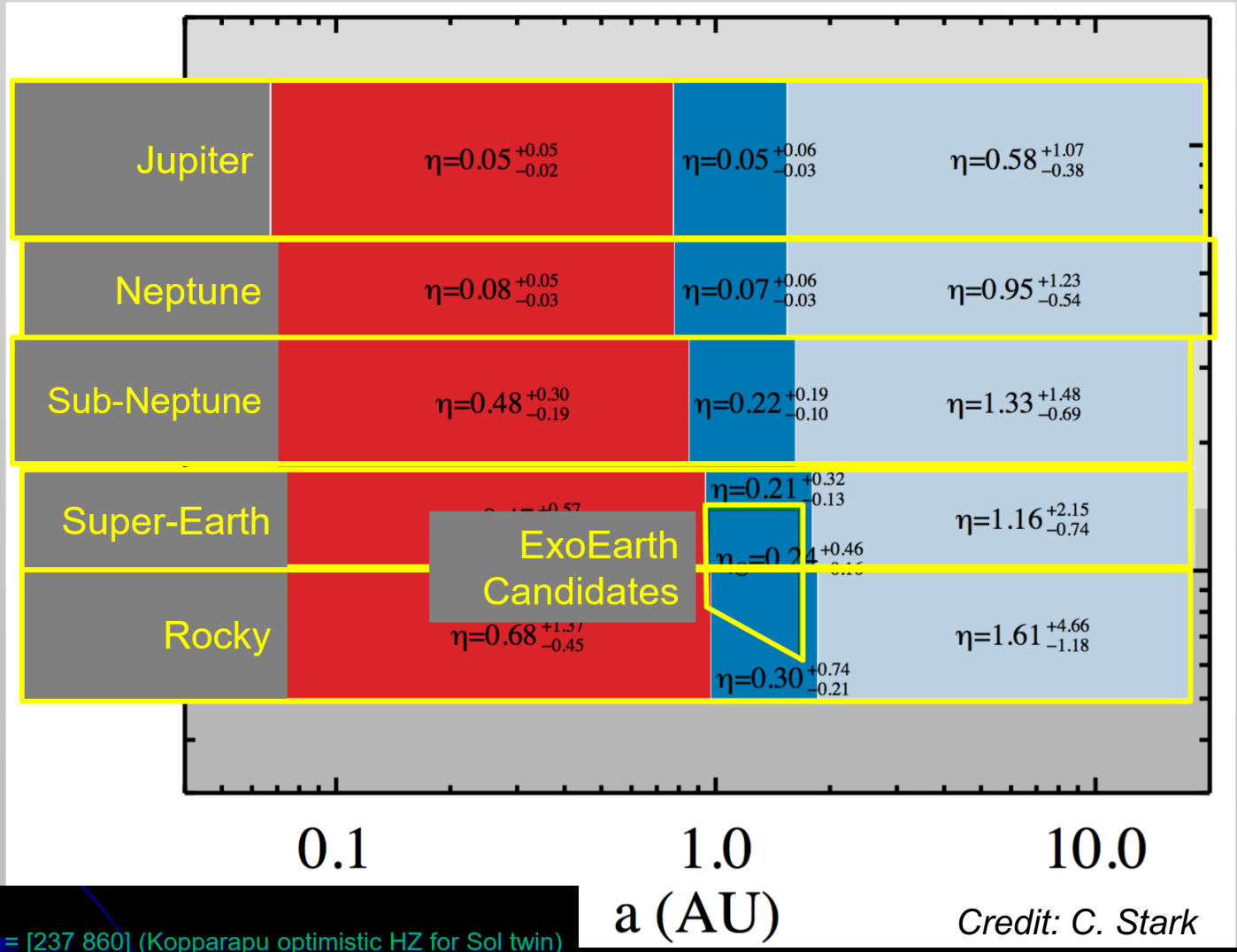


Credit: NASA/Kepler/F.Fressin

Frequency of ExoEarths in Habitable Zone

Per Exoplanet Program Analysis Group, based on Kepler results

We use the SAG13 continuous distribution, but adopt coarse grid to communicate results:



$\eta_{habSol,SAG13}$

- R = [0.5 – 1.5], P = [237 860] (Kopparapu optimistic HZ for Sol twin)

20

Large Binocular Telescope Interferometer

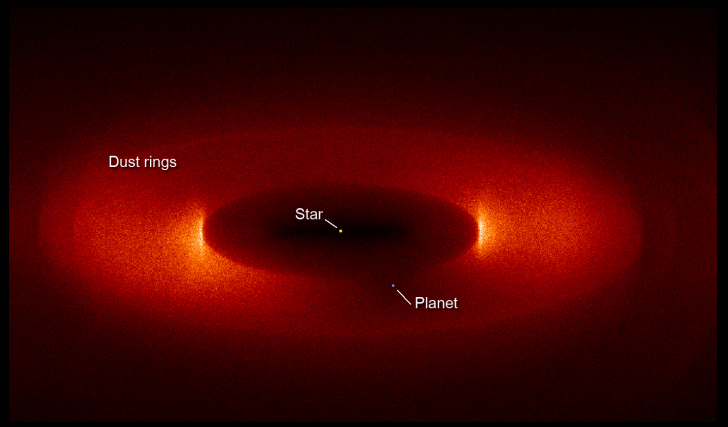
Measuring HZ Exozodiacal Dust to Inform Designs of Future Missions

Credit: ESO/Y. Beletsky

- 35-stars observed
- NASA survey completed June 2018
- Paper by S. Ertel accepted by ApJ on first 30 stars
- Result: majority of stars in survey are *not dusty (median level ~<20 Zodi)*

Phil Hinz, PI

THE UNIVERSITY OF ARIZONA



Credit: NASA/GSFC

NN-EXPLORE NEID

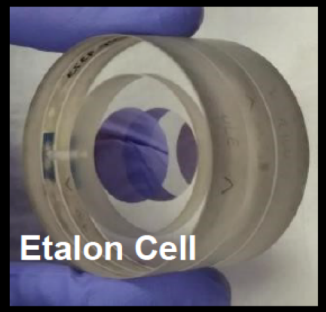
NASA-NSF Exoplanet Observational Research

PennState

PI: S. Mahadevan

- Precision radial velocity spectrograph (goal 27 cm/s) at the WIYN Telescope, Kitt Peak
- Status:
  - Facility construction nearly complete
  - Next Steps: Coating of off-axis paraboloid, delivery of blue arm of laser frequency comb, delivery of port adapter
- Plan for commissioning August 2019
- NOAO Provides:
  - GO 90 nights per year, start 2019B
  - GTO 30 nights per year for 5 years
  - NExScI will provide the automated RV pipeline and archive database

NEOS Camera

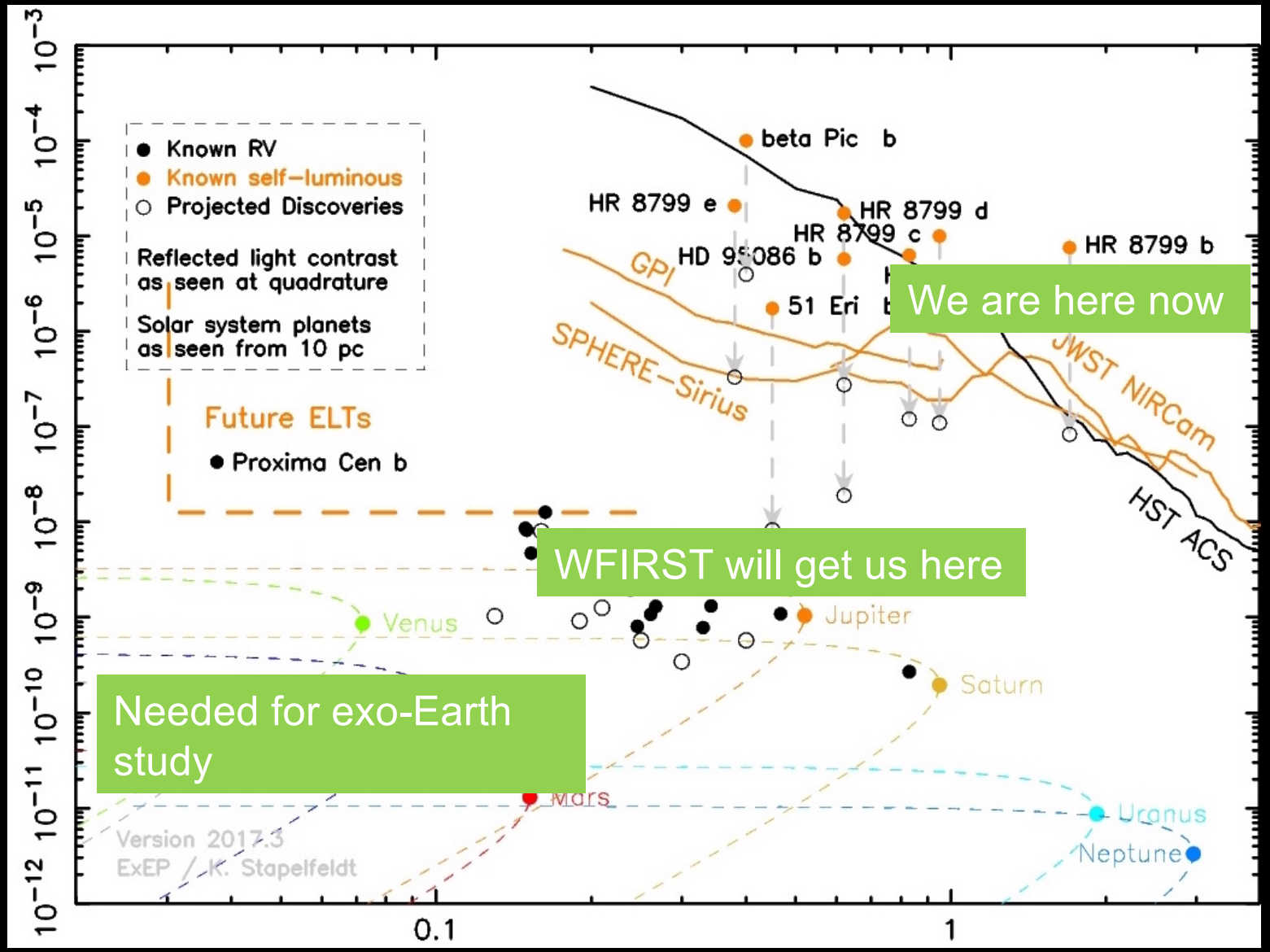


Program Investments

Ground Science that Furthers NASA Level 1 Requirements

- NExScI is providing access to **HIRES PRV data reduction pipeline** (contact: David Ciardi)
  - Initial release Sept 28 2018, for use with data 2019A forward
  - Subsequent release provides analysis of earlier data
- NASA and NSF providing support to **US Access to Southern RV** – starting 2019A (contact: David Ciardi)
  - CHIRON on the SMARTS 1.5m telescope – 40 nights/semester
  - Complements Keck/HIRES and WIYN/NEID
  - Augmentation of existing NN-EXPLORE program
- Continue community access to **speckle high resolution imaging** (contact: Steve Howell, ARC; David Ciardi, NExScI)
  - Stellar characterization of TESS candidates Three speckle instruments available to the community through NOAO
  - WIYN/NESSI (39 mas), Gemini-N/'Alopeke (17 mas), Gemini-S/DSSI

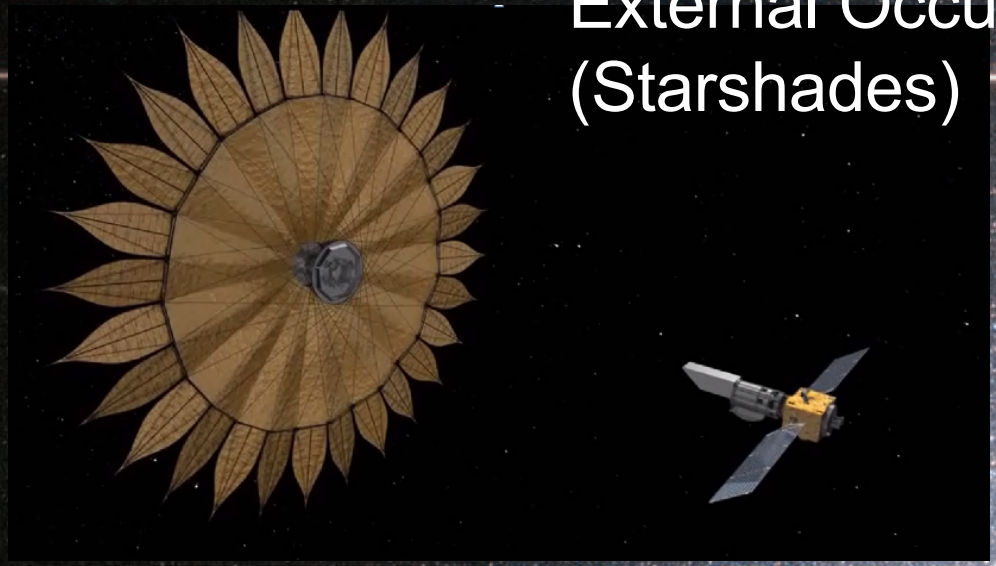
Challenge to Directly Image Exo-Earths

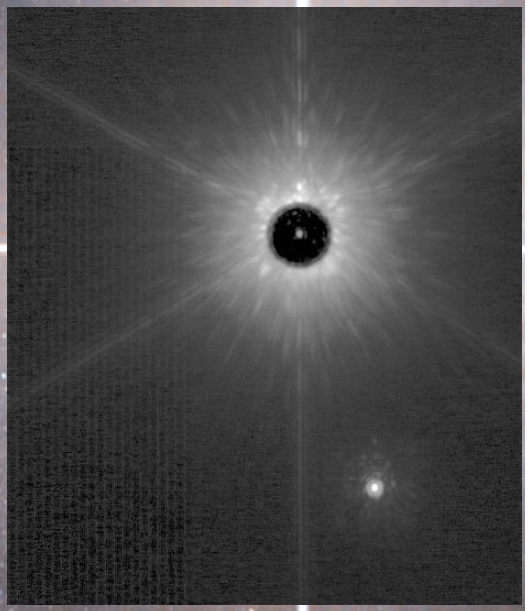


Starlight Suppression

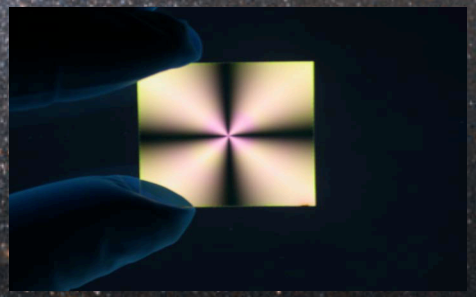
The Key to the Search for Life on Earth-sized Exoplanets

External Occulters
(Starshades)

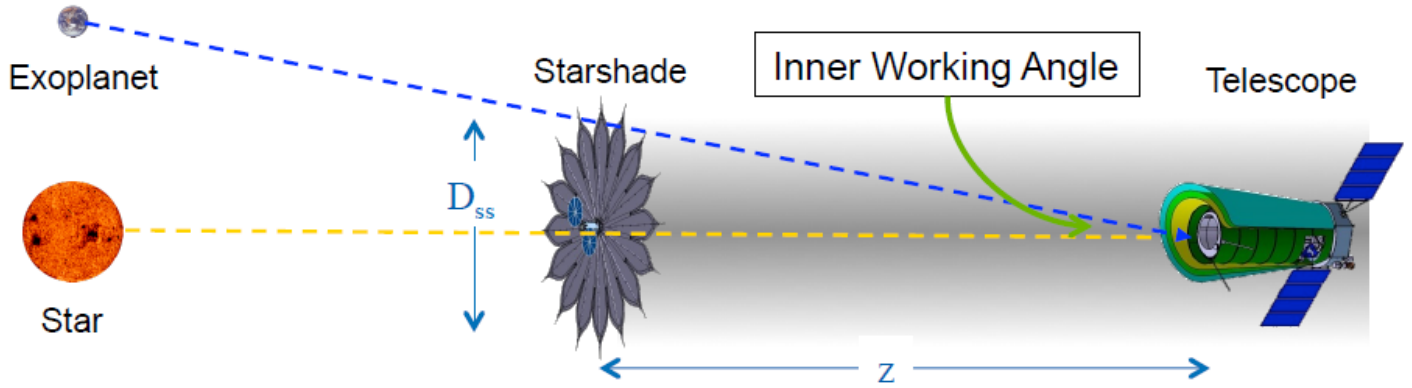




Internal Occulters
(Coronagraphs)



Starshade concept



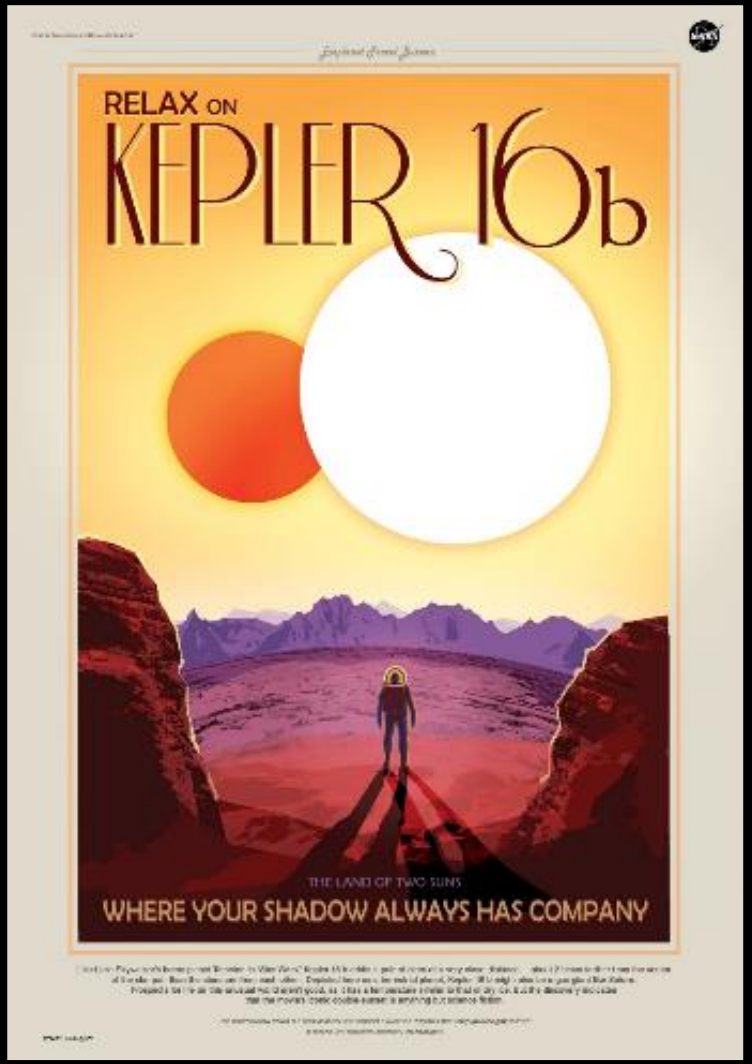
- Inner Working Angle is the closest separation of Planet and Star that we can expect to see with a given starshade
- For Hypergaussian starshade, this is approximately equivalent to:

$$IWA = \frac{D_{SS}/2}{z}$$

Credit: Steve Warwick, NGST

Exoplanet Communications

Explore a Galaxy of Worlds, Inspiring our Own



Exoplanet Travel Bureau

"All the News That's Fit to Print"

The New York Times

Late Edition

Today, patchy morning fog, partly sunny, warm, high 64. Tonight, mostly cloudy, mild, low 52. Tomorrow, clouds and sunshine, showers, high 66. Weather map is on Page B8.

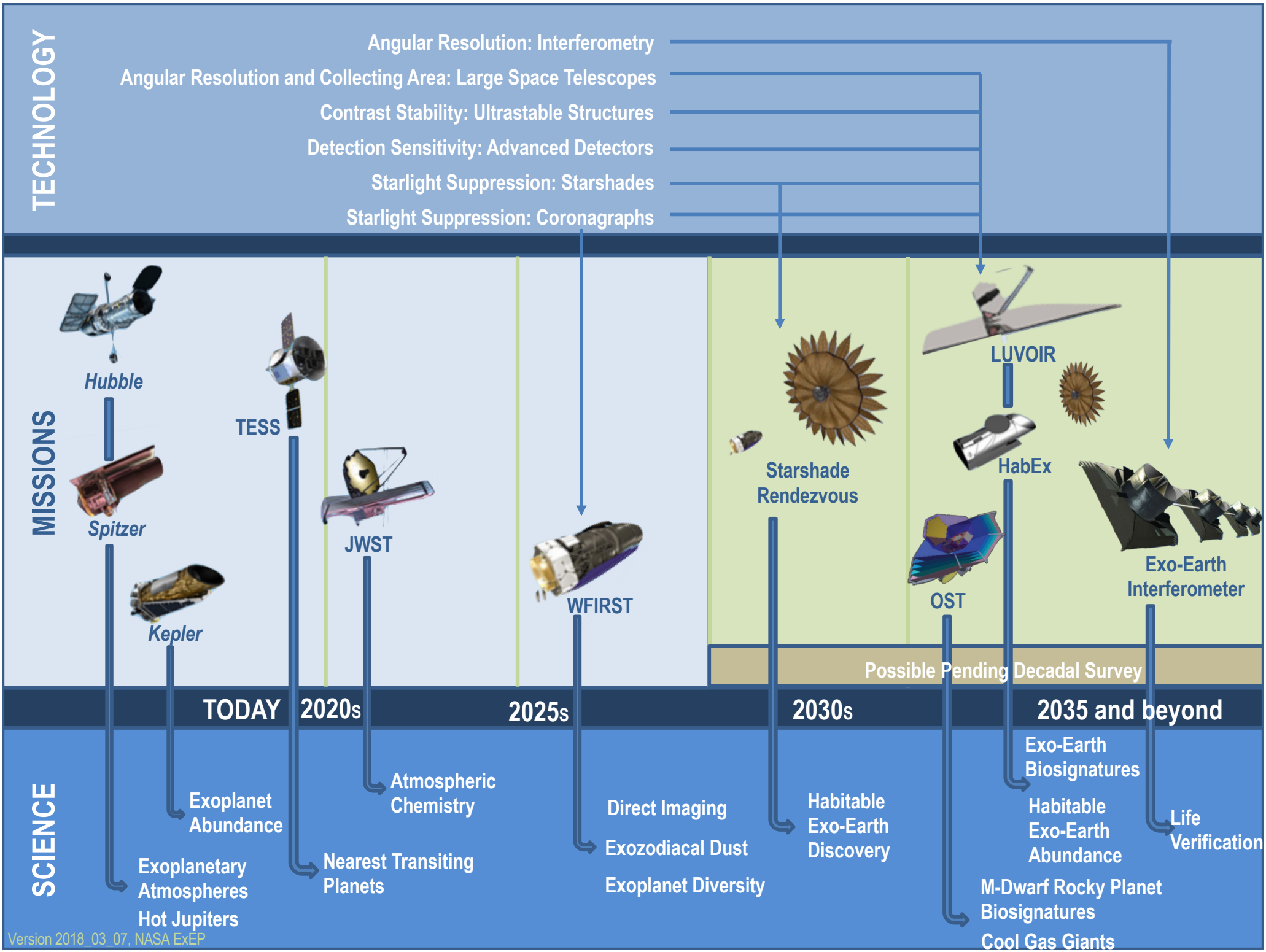
VOL. CLXVI . . . No. 57,517 © 2017 The New York Times Company NEW YORK, THURSDAY, FEBRUARY 23, 2017 $2.50

A rendering of newly discovered Earth-size planets orbiting a dwarf star named Trappist-1 about 40 light-years from Earth. Some of them could have surface water.

“EXOPLANET EARTH” EDITION OF TRAPPIST-1

Connecting exoplanet Science Enthusiasm to our own World

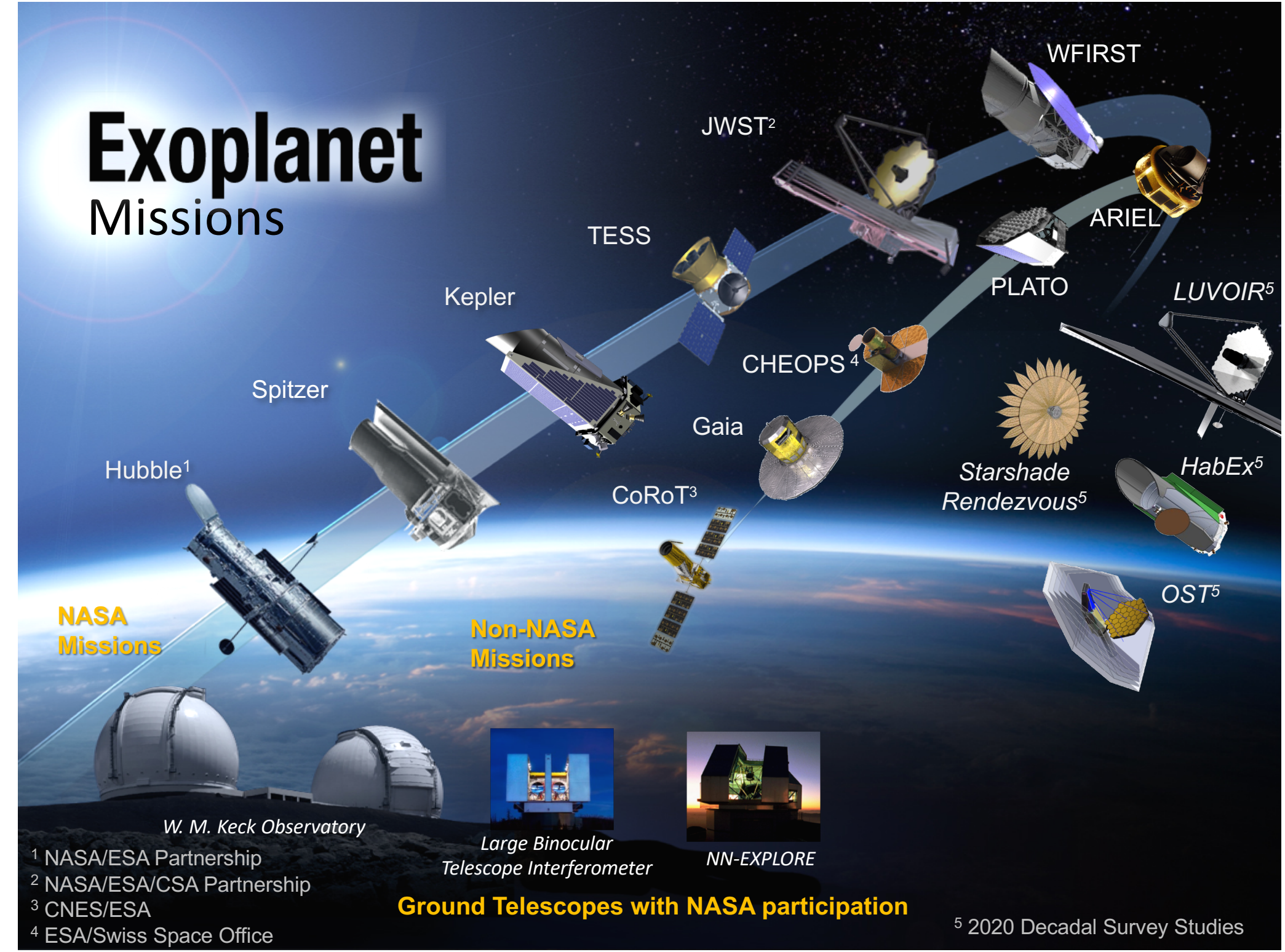
Sun and Alpha Centauri system appear as ~5th mag naked eye stars in Leo from TRAPPIST-1


TECHNOLOGY
Angular Resolution: Interferometry
Angular Resolution and Collecting Area: Large Space Telescopes
Contrast Stability: Ultrastable Structures
Detection Sensitivity: Advanced Detectors
Starlight Suppression: Starshades
Starlight Suppression: Coronagraphs
MISSIONS
Hubble
Spitzer
Kepler
TESS
JWST
WFIRST
Starshade Rendezvous
LUVOIR
HabEx
OST
Exo-Earth Interferometer
Possible Pending Decadal Survey
TODAY
2020s
2025s
2030s
2035 and beyond
SCIENCE
Exoplanetary Atmospheres
Hot Jupiters
Exoplanet Abundance
Nearest Transiting Planets
Atmospheric Chemistry
Direct Imaging
Exozodiacal Dust
Exoplanet Diversity
Habitable Exo-Earth Discovery
M-Dwarf Rocky Planet Biosignatures
Cool Gas Giants
Exo-Earth Biosignatures
Habitable Exo-Earth Abundance
Life Verification
Version 2018_03_07, NASA ExEP

Updates to 2015 Exoplanet Probe Studies

Short white papers requested by NASA HQ June 2017, delivered Nov. 2017; led by Stapelfeldt & Mamajek with inputs from STDT alumni

Exoplanet Missions



[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA
[4] ESA/Swiss Space Office

Ground Telescopes with NASA participation

[5] 2020 Decadal Survey Studies

Jet Propulsion Laboratory
California Institute of Technology

exoplanets.nasa.gov

Acknowledgements

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

- Work was also carried out at NASA's
  - Ames Research Center
- Work was carried out as well under contracts with the National Aeronautics and Space Administration and
  - Princeton University
  - University of Arizona
  - National Optical Astronomy Observatory (NOAO)
  - Pennsylvania State University
- Contributions from ExEP program leadership and staff gratefully acknowledged